Software Environment for Investigating Decentralized ATM Concepts

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Outline

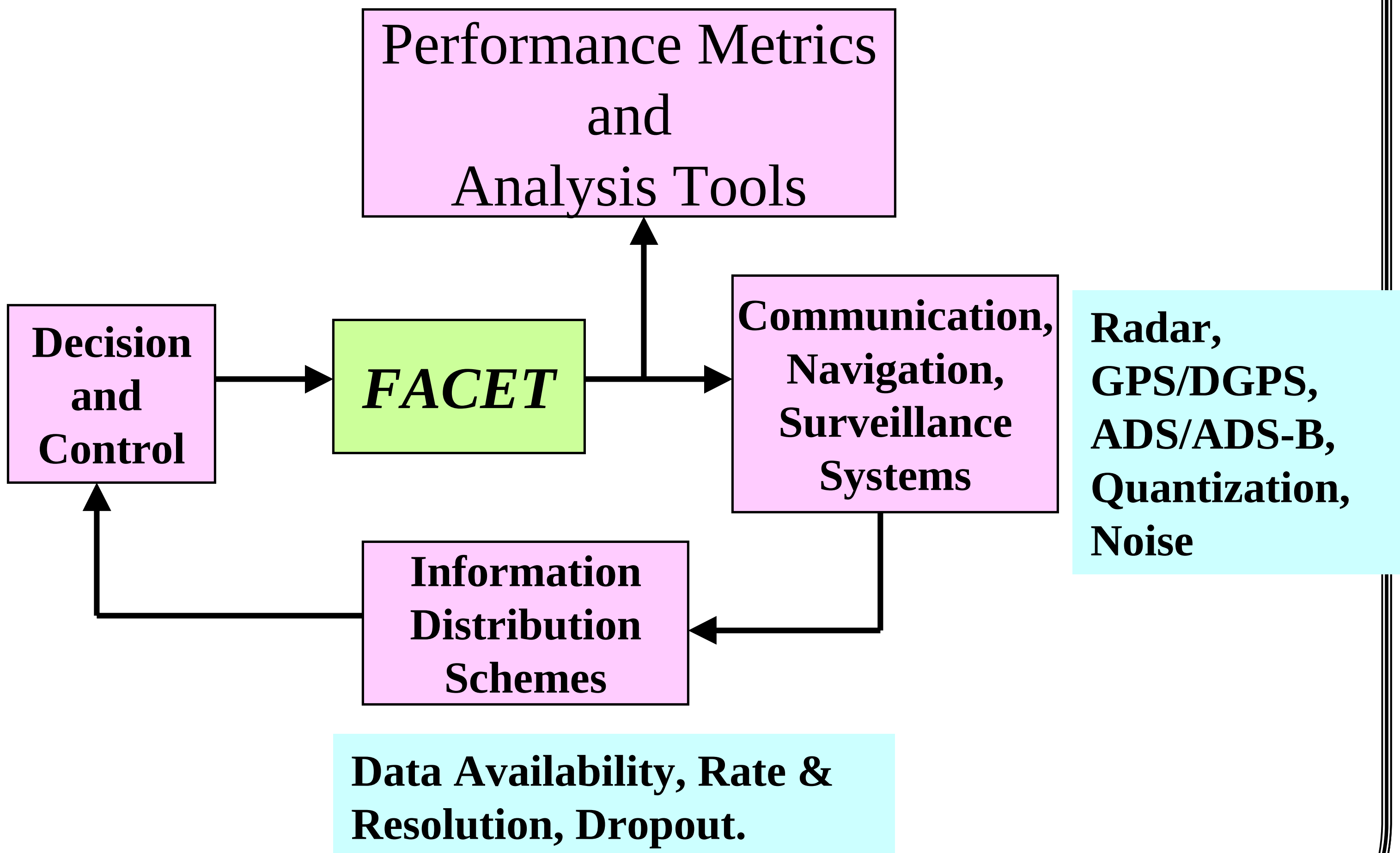
- **Motivation**
- ***SEAMA**** **Components and Issues**
- **Control-Theoretic Formalism for ATM Analysis**
- **Case Study: DAG Conflict Resolution**
- **Summary and Future Work**

*Software Environment for Air-Traffic Management Analysis

Need for *SEAMA*

- **Several Airborne Flight Conflict Resolution Algorithms Continue to be Developed:**
  - **Optimization, Potential Fields, Rule-Based, Fuzzy Logic, Genetic Search, Neural Networks**
- **These Methods will have to be Integrated with Ground-Based Air Traffic Conflict Resolution System.**
- **Need to Assess Performance and Robustness of Airborne and Air-Ground Integrated System.**
  - **Distributed Control System.**
- **Need a Rich and Realistic Environment for Modeling and Modifying Distributed Conflict Resolution Algorithms.**

Software Environment for Air-Traffic Management Analysis (*SEAMA*)



SEAMA Software Development Issues

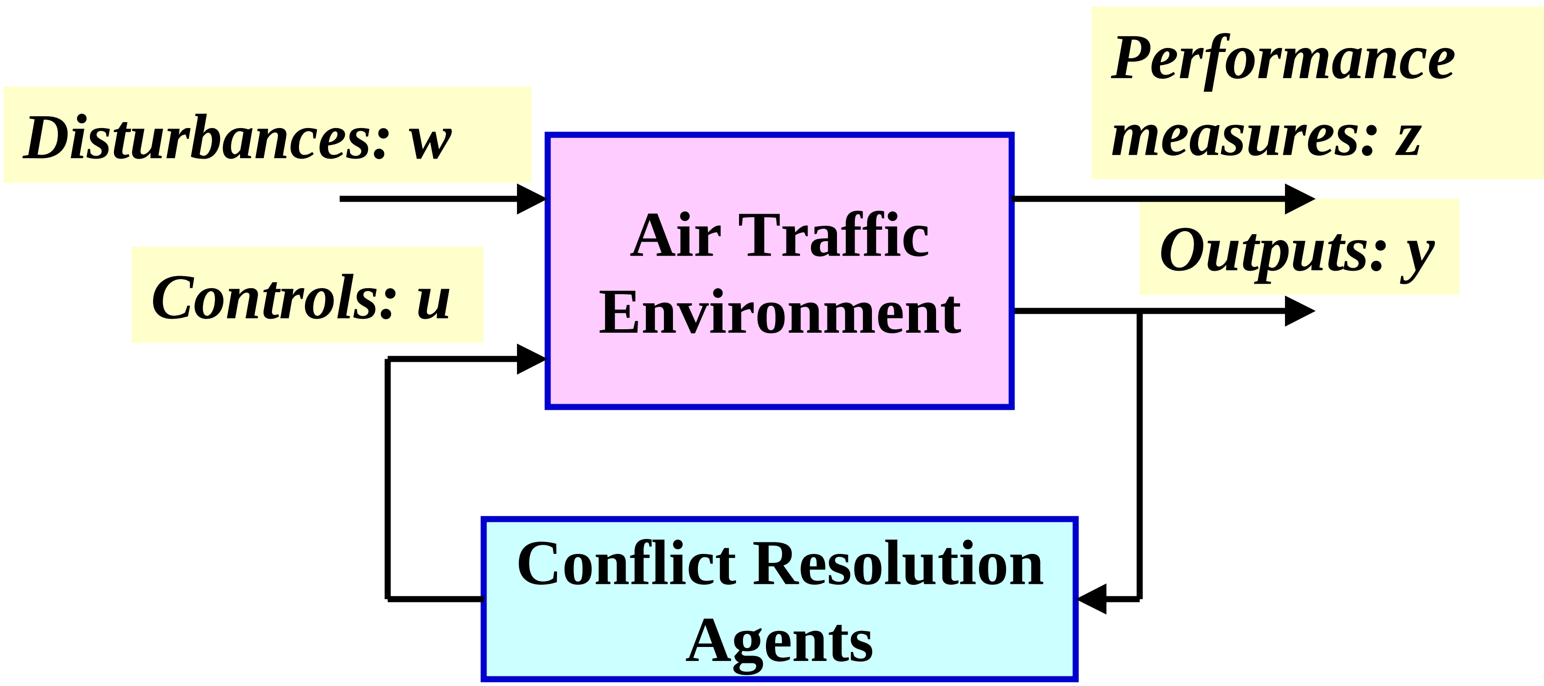
The Software Environment Must:

- Allow Rapid Coding and Debugging Features.
- Match the Complement of Software Tools Currently Being Used by Researchers.
- Provide Simple Methods for Data and Algorithm Exchange.
- Provide Capabilities for Algorithm Security in Order to Permit Comparative Evaluations.

- **MATLAB®/Simulink®** Software Environment Satisfies these Requirements.

Analysis Using Concepts from Control Theory

ATM as a Closed-Loop System (Robust Control):



$$x_{i+1} = x_i + f(i, x_i, u_i, w_i),\ y_i = g(i, x_i, u_i, w_i), z_i = h(i, x_i, u_i, w_i)$$

$$u_i = K(i, y_i, y_{i-1}, \ldots)$$

$$f(\ldots), g(\ldots), h(\ldots), K(\ldots) \text{ are Complex Computer Programs}$$

Control Theoretic Characterization of the Air Traffic Management System

Definitions:

***States (x)*: Position and Velocity Vectors of all the Aircraft in the Environment (Knowledge of these Completely Characterizes the Air Traffic Environment)**

***Controls (u)*: Air Traffic Control Advisories to the Aircraft in the Environment**

***Disturbances (w)*: Wind, Ambient Temperature, Data Drop-out/Noise, Communication Channel Limitations, Subsystem Failures (Computer, Radar, Communication Links), Increase in Traffic Volume,……..**

***Outputs (y)*: Data Available to Carry Out Air Traffic Management.**

***Performance Measures (z)*: Variables that Characterize ATM System Efficiency and Safety.**

Desirable Properties of Robust Closed-Loop Systems

- **A Robust Closed-Loop System Must be:**

a) *Dissipative* (Nonlinear Robust Control Theory, Helton and James 1999)

A System is γ-Dissipative if there exist a $\gamma > 0$ and a function $\beta(x_0) \geq 0$ with $\beta(0)=0$, such that

$$\frac{1}{2}\sum_{i=0}^{n}\left|z_i\right|^2 \leq \gamma^2 \frac{1}{2}\sum_{i=0}^{n}\left|w_i\right|^2 + \beta(x_0)$$

$$\textit{for all } w \in L_{2,n} \textit{ and for all } n$$

i.e., the Nonlinear input-Output Map: $w \mapsto z$
has finite L_2 Gain with a Bias Term Due to the Initial State.

In Linear Dynamic Systems, *Dissipativity* is the H^∞-Norm of the System Transfer Function z(s)/w(s).

b) Stable in the Lyapunov Sense

Stability and Robustness

Working Definitions:

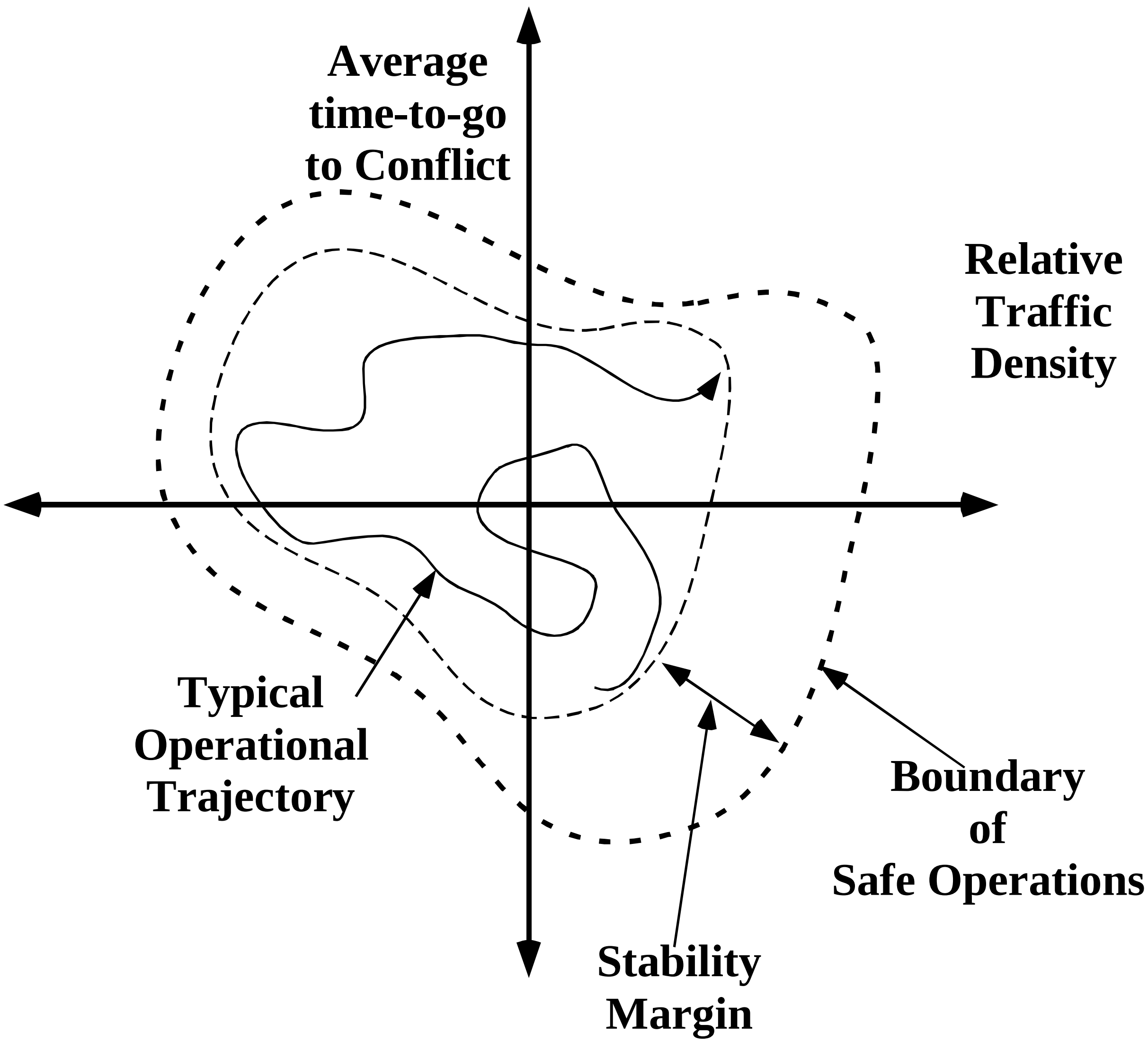
Describes the Desirable Temporal Behavior of the Environment.

- **Stability: Tendency of the System to Move Towards Desirable Operating Conditions After Being Perturbed.**

- **Robustness: Tendency of the System to Maintain Stability Under Disturbances and Variations in System Parameters.**

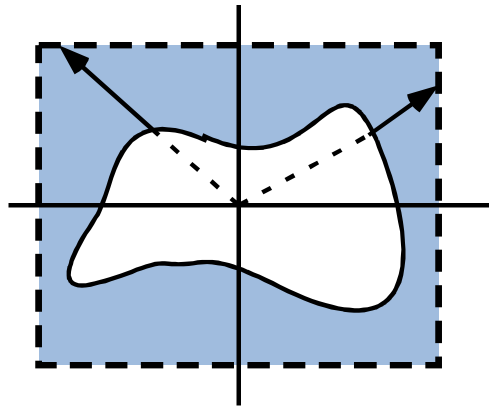
- **Meaningful only in Terms of the Performance Variables (Output Stability) in Finite Time.**

Lyapunov Relative Stability Measure

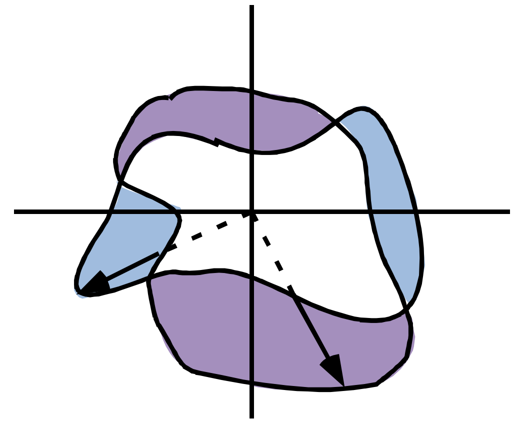


Stability and Distance Measures

Margin



Set Distance



Several distance measures implemented:

- Mean-squared radial separation
- Maximum radial separation
- Minimum radial separation
- Set distance (Hausdorff metric):

  $h(A,B) = \max(d(A,B), d(B,A))$, where

  $d(A,B) = \max\{d(x,B): x \text{ in } A\}$, $d(x,B) = \min\{d(x,y): y \text{ in } B\}$
- Volumetric free space (margin only):

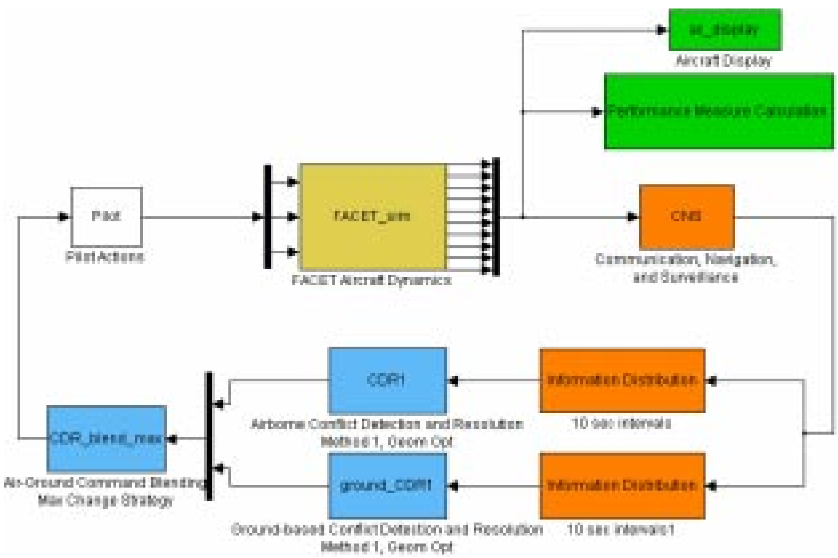
  1 - volume (area) enclosed by curve or surface / volume (area) enclosed by margin boundaries

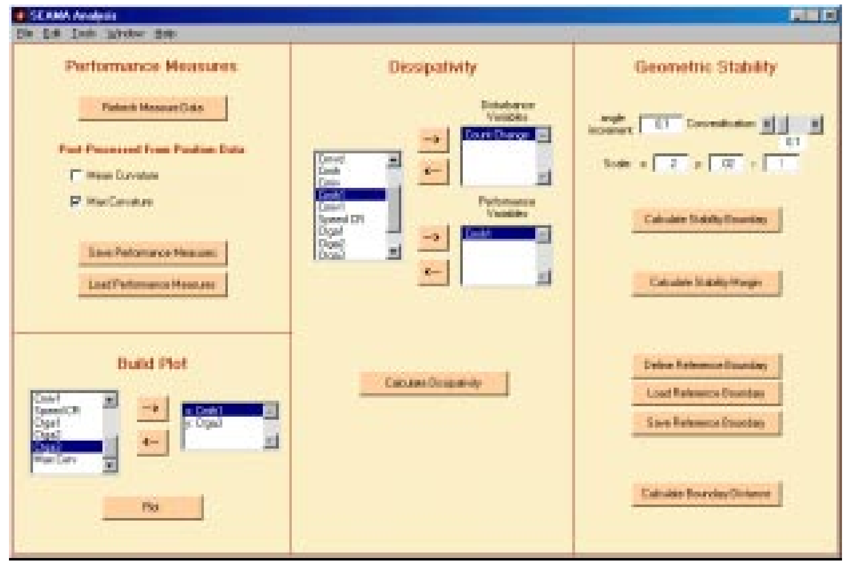
Air Traffic Performance Parameters

- aircraft count, change in aircraft count
- C_{mhd} and C_{mvd} (inverse mean weighted horizontal and vertical separation)*
- C_{vg1}, C_{vg2}, and C_{vg3} (speed standard deviation, contrast ratio, and mean)*
- C_{mih} and C_{miv} (inverse average minimum horizontal and vertical separation)*
- C_{mih1} and C_{miv1} (inverse minimum horizontal and vertical separation)*
- C_{tga1} (# pairs with time to go <5 min)*
- C_{tga2} and C_{tga3} (average and minimum time-to-go)*
- Average curvature
- Maximum curvature
- fractal dimension (“meta” performance measure)

*Implemented using code from Dr. Gano Chatterji, based on measures in Chatterji & Sridhar, “Measures of Airspace Complexity”

SEAMA: Software Demo





Case Study: DAG-Conflict Detection and Resolution

Two techniques from *FACET* implemented as Simulink blocks:

CDR1: Geometric Optimization (C implementation)

CDR2: Potential Field (MATLAB function implementation)

- Airborne CDR2: same as *FACET* implementation
  - surveillance zone of 100nm
  - separation red zone of 5.1nm
- Ground-based CDR2: significantly more conservative
  - surveillance zone of 150nm
  - separation red zone of 10.1nm

ATM Command Integration:

Maximum Change

MAX(Ground Command, Airborne Command)

Weighted Sum

SUM(60% ground, 40% airborne)

Case Study: DAG-Conflict Detection and Resolution

CDR2 Technique (Potential Field): With Weighted Sum Ground/Air Command Blending

Dissipativity Measures: (*w* = count w.r.t. moving average):

Blending Scheme	Dissipativity 1 (min sep)	Dissipativity 2 (min t-to-go)	Dissipativity 3 (speed CR)	Dissipativity 4 (max curv)
Air Only	3.0224	0.0920	6.2357	2.8240
Ground Only	2.0378	0.0920	6.2357	2.8240
Sum	2.5711	0.0920	6.2357	2.8240

Note that in this example the ground conflict resolution scheme uses a larger safety zone (10.1 nm) around the aircraft than does the airborne scheme.

Case Study: DAG-Conflict Detection and Resolution

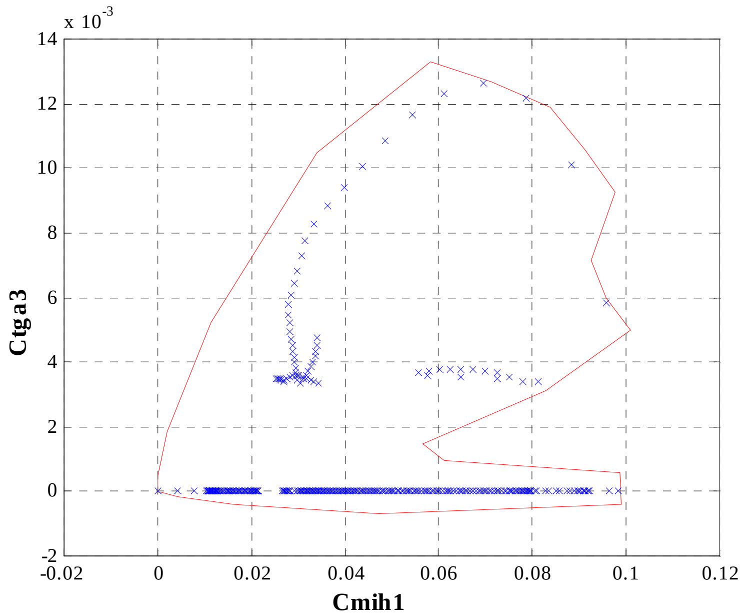
CDR2 Technique (Potential Field): With Weighted Sum Ground/Air Command Blending

Stability Margins:

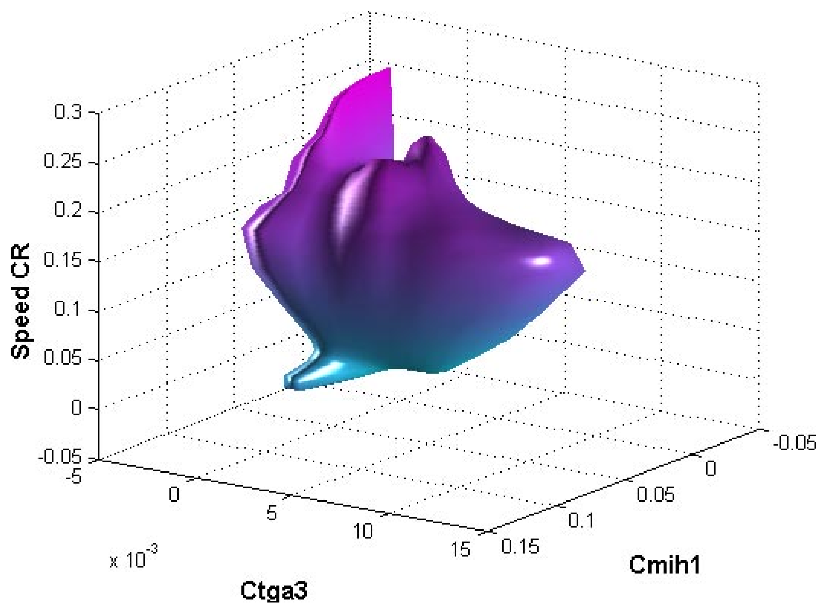
Blending Scheme	**Performance Measures**	**Margin 1 (max radial)**	**Margin 2 (volumetric free space)**
Air Only	min sep & min t-to-go	0.1452	0.7072
Ground Only		0.1921	0.9252
Sum		0.1527	0.8847
Air Only	speed CR & max curv	3.9573	0.9250
Ground Only		3.7064	0.9108
Sum		3.8301	0.9269
Ground Only	min sep & min t-to-go & speed CR	4.8481	0.9976
Sum		4.8462	0.9973

Case Study: DAG-Conflict Detection and Resolution

Stability Bounding Surfaces, CDR2 with Weighted Blending



Min sep and min t-to-go



Min sep, min t-to-go, and speed CR

Presentation Summary

- **Software Environment for Air-Traffic Management Analysis (*SEAMA*):**
  - ***Distributed Air-Ground Air Traffic Conflict Resolution.***

- **Notions of Stability Margins, Dissipativity and other Robustness Measures.**

- **Case Study: Integrated Air-Ground Conflict Resolution**

- **Next Step:** **Numerical Implementation of Concepts from Decentralized Control Theory**

  - **Structural Controllability and Observability**
  - **Connective Stabilizability and Stability (Graph Theoretic Methods)**
  - **Connective Robustness Measures**
  - **Distributed-Interconnected Observer Theory**